Development of Next-Generation Underwater Construction Machinery

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1. BACKGROUND

Generally speaking, as the scale of port construction works is huge, various dredgers, crane verges, and working crafts have been used up until now. However, Japanese breakwaters are known as composite type breakwaters, as shown in Fig.1, which are constructed by first establishing a rubble mound foundation on the sea bottom, and then placing a concrete caisson on that foundation after leveling off the surface of the mound. Consequently, it is necessary for divers to be able to do many different underwater jobs in the construction of breakwaters. Fig.2 shows the jobs assigned to divers.

Recently, because of an increase in large ships, ports must be both larger and deeper. Moreover, short construction periods are desirable. In addition to this, it is necessary to have several ports in other places in preparation for large-scale disasters, like earthquakes and typhoons. Owing to these conditions, underwater construction work requires mechanization to ensure high efficiency and guarantee the safety of the divers who are working deep.

2. RECENT SITUATION OF UNDERWATER CONSTRUCTION MACHINERY

2.1 Large rock mound leveling machines and compact backhoes

As mentioned above, recent port construction work is performed on larger scales and at deeper sea levels than they used to be. Therefore, rock mound foundation leveling machines were initially developed by the Port Construction Bureau of Japan and introduced to actual construction sites with a working depth of 25m in the Kamaishi Bay Mouth Breakwater project for tsunamis. Some commercial companies followed this lead, and various kinds of rock mound foundation leveling machines were developed. However, as these rock mound foundation leveling machines are extremely large, they only just manage to cover their costs in the case of large scale projects.

On the other hand, backhoes with a wide variety of dimensions are being used in ground construction work. As the width of the minimum size is that of one person, backhoes are used in small places that can accommodate no more than a single person. As a direct result of this, we no longer see shovels operated nowadays by human labor, as backhoes are considered to be an all-mighty item of equipment for construction work.

For this reason, the underwater backhoe with a diver on the machine to act as an operator was developed. This development was started in Okinawa, in the southern part of Japan that boasts clear seawater, and has been carried out for some years. The prototype consisted of a normal used backhoe that was remodeled to be waterproof and from which the power unit was removed and reinstalled on the mother ship(Fig.3).

With regards to power sources, the electric-hydraulic model and the diesel engine-hydraulic model are available. Some of them even use vegetable oil to prevent water pollution. More than 10 backhoes developed by three different companies are at work at the moment. The working depth is -30m.

2. 2 Main underwater backhoes operations

Underwater backhoes are capable of carrying out the four operations shown in Fig.4.

①Scrape in (main operation)

The arm is initially extended to its fullest extent, and the cylinder is then retracted to scrape the rock into the bucket. Next, the arm is swung around and retracted further into the body, and then extended again to throw out the rock. This is the main leveling operation of the backhoe, and it moves rocks from convex place to concave places.

②Pushing

The rock is pushed out of the back of the bucket by teeth when the arm is fully extended away from the body. This is suitable for moving rocks that are susceptible to rolling on the surface of the mound.

③Stumping

The teeth or back of the bucket are used to pound the rock in order to force it into concave places and compact it firmly together with other rocks.

④Swing

This operation is not recommend owing to the structure of the backhoe. The rocks are moved to the side of the bucket during the swinging motion. This is suitable for moving rocks that are susceptible to rolling on the surface of the mound.

3. REMOTE-CONTROLLED UNDERWATER CONSTRUCTION MACHINERY DEVELOPMENT PLANS

3.1 Experimental remote-controlled underwater backhoe plans

As mentioned above, the Ministry of Transport and other commercial companies are planning the development of remote-controlled underwater backhoes that will have many advantages. This remote-control technology can also be adapted to other types of underwater construction machinery. The specifications of a certain type of remote-controlled underwater backhoe are shown in Table 1. This type of backhoe already exists and is equipped with many sensors specifically designed for this purpose. The field tests will be carried out at the end of 2000.

3.2 The necessity of remote-controlled underwater construction machinery and the concept behind it

The necessity of remote-controlled underwater construction machinery is explained below in comparison with operator-assisted underwater backhoes

①The operator must have the two licenses, one for diving and another one for operating the backhoe.

②In addition to this, many operators are frequently required to work on deep construction sites, as the working time of divers decreases in accordance with water depth.

③ The structure of the cockpit of the existing underwater backhoe is designed to allow easy escape, but in the worst case, it is possible that the backhoe is turned over by unexpected fast water current.

Therefore, underwater construction machines should be remotely controlled by operators on board ship or on land.

In order to operate an underwater construction machine remotely, it is necessary for the operator to be provided with an equivalent amount or more information than is currently available to underwater backhoe operators. This is because manned underwater backhoes are operated by experienced divers who have an excellent knowledge of undersea conditions, but there is a possibility that remotely-controlled machine operators may be inexperienced owing to problems arising from the supply and demand of labor. However, as it is difficult to perfect man-machine interfaces right from the start, remotely-controlled backhoes using mainly visual images are being planned, as man acquires most of the information he requires through his eyes. These visual images are obtained through an ordinary underwater TV camera and a underwater ultrasonic camera using acoustic holography. Using these vision systems, experienced operators control the underwater backhoe while relying on the experience that have gained underwater.

The reason why two kinds of vision system are used is to take advantage of the merits of normal TV cameras and underwater ultrasonic cameras. In other words, visibility in turbid water with normal TV cameras is not good but provides high resolution, and turbid water does not affect underwater ultrasonic cameras, although they only have a small number of pixels. The underwater ultrasonic camera was developed by the Port and Harbour Research Institute mentioned below.

The position of the underwater backhoe is measured with an SBL (Short Base Line) positioning system situated on the bottom of the mother ship. This mother ship has two sets of RTK-GPS in order to clarify its direction.

An angle meter is attached to each articulation of the arm on the underwater backhoe to measure the articulation angle in order to acquire the posture of the arm. The angle of rotation of the body is also measured by an angle sensor, and inclinometers are attached to the body to discover its level of inclination. Thus, all values relating to position, direction, arm posture, body angle and inclination are measured, enabling a 3-D image of the backhoe to be constructed. This image will be superimposed with an image of the sea bottom measured beforehand with a multi-beam sonar shown in Fig.5. However, in this image, the position and motion of the backhoe will be renewed but the sea bottom image will remain static.

3.3 Underwater ultrasonic camera

Regardless of whether an underwater construction machine is large or small, it needs some form of underwater vision system. However, it is not necessary for all underwater construction machinery to be fitted with high-performance and expensive underwater vision systems. It is therefore necessary for underwater construction machines that needs underwater vision systems to be carefully selected, and the required performance must be estimated strategically.

An underwater ultrasonic imaging system that enables objects to be seen in turbid water is currently undergoing development at PHRI. The purpose of this development is to acquire images with which to operate remote-controlled underwater construction machines. In turbid water, optical visibility is limited because light is both attenuated and scattered. But acoustic waves have the ability to go through turbid water that normally prevents optical systems from obtaining vision.

This system consists of a transducer unit and a control unit. It has a receiving array of 114 elements measuring 300×300mm, and an acoustic projector in the center of the receiving array.
The ultrasonic frequency is 600kHz. This system, which uses acoustic holography, will be able to acquire real-time 3-D images. The 3-D images can be reconstructed by mean of a single transmitting and receiving process. The operating range for distance purposes is 1 to 10m, and the field of view is 80×80cm at 10m.

Experiments were carried out with this imaging system in a water tank. The 2-D acoustic image of the objects (balls in the shape of a "A") acquired at a distance of 9m is shown in Fig.6.

4. DEVELOPMENT OF NEXT-GENERATION UNDERWATER CONSTRUCTION MACHINERY

4.1 The necessity of developing next-generation underwater construction machinery

As mentioned above, the first experiment will be carried out at the end of 2000 by experienced operators. As the number of the available operators with experience is small, it is necessary to provide the operator with more information on underwater conditions than usual in order to allow him to operate the remote-controlled backhoe. The more underwater information provided enables even beginners to operate the underwater backhoe, and allows experienced operators to operate it both easily and more efficiently.

There is no necessity for the operating device to be similar to that of the underwater backhoe at present. A bilateral master slave manipulator, similar to the backhoe arm or joy stick, may be introduced.

The purpose of this next-generation underwater construction machine is to enable the operator on the mother ship or the ground to obtain the same sense and operability as if he was actually on the underwater construction machine in clear water.

4.2 Force sensing

It is extremely difficult for the machines to operate freely in port construction areas only with ordinary vision systems.

Measuring force by the motion of the underwater construction machine with certain instrumentation and then feeding the results back to the operator is very helpful for the operator. Recently, compact 6-axis force feedback systems are available on the open market, and the fundamental research into these that has been carried out at PHRI are shown in Fig.7.

4.3 Position and posture

The position of the underwater backhoe is measured with an SBL (Short Base Line) positioning system fitted to the bottom of the mother ship. The mother ship is equipped with two sets of RTK-GPS in order to clarify its direction. These are the same as explained for the experiment that is due to be carried out at the end of 2000.

If the body angle of the underwater backhoe is not shown on the CRT but the operator's seat moves at the same angles, the operator is able to physically feel the inclination to enable easier operation.

4.4 Auditory sense

A survey of divers indicated that they are aware of the force to the rock by the intensity of the sound of the hydraulic motor. An underwater microphone will provide the operator with useful information. However, the auditory sense may be replaced by the force feedback system because it shows direct force.

4.5 Man-machine interface

By constantly displaying the underwater backhoe and the sea bottom on the CRT, and for example, the part bigger than planned design is colored blue and the part smaller than planned design is colored red. Thus operation will be simplified, and the results are used for inspection purposes. Owing to this, it is imperative that the backhoe positioning is accurate.

The position of the underwater backhoe will constantly be measured with two sets of SBL (Short Base Line) positioning systems fitted to the bottom of the mother ship. The graphics on the CRT will be renewed according to the motion and position of the backhoe and the configuration of the sea bottom, which is measured by a constant multi beam sonar, in order to give the operator more real-time maneuverability (virtual reality). As the result of this, the total man-machine interface will be completed as shown in Fig.8. This will lead to a vast improvement in remote control maneuverability.

5. FUTURE PLAN

In the near future, almost all the underwater construction work will be mechanized, and the main machine for this will be the underwater backhoe. The modifications to enable the end-effector to use underwater backhoes as grabbers has already been completed. Additional modifications will be made to the end-effector in order to expand the performance of the underwater backhoe.

Tele-existence technology will become more reliable through the introduction of sensor fusion technology and virtual reality technology. As the result, even in the case of remote-controlled operations, the operator will be able to obtain the sensation that he or she is working on the ground.

The last problem may be a financial one. To solve this problem, it could be helpful to remodel mass-produced ground machines, manufacture underwater models with compatible parts, and supply suitable models to the construction sites.

To realize these solutions strategically, it is necessary to estimate future underwater port construction work and acquire a firm understanding of port construction schedules.

Reference

Tadahiko YAGYU · Keiji OOMIYA:Development of Underwater Construction Machine, July 1997, Journal of the Japan Society of Civil engineers, pp.18-20

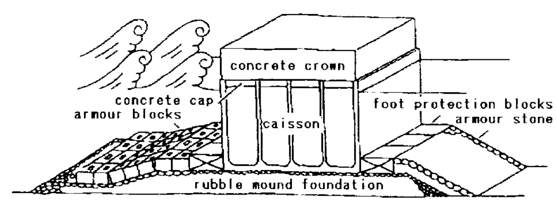

Fig.1 Composite Type Breakwater

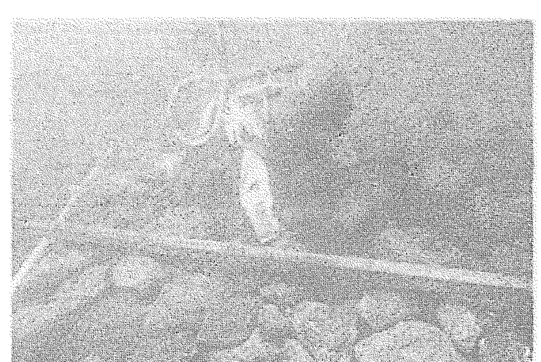

Fig.2 Divers Duties

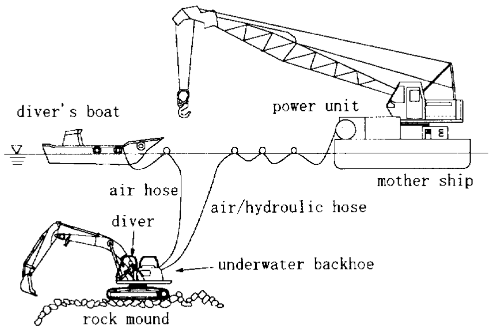

Fig.3 Underwater Backhoe with Operator

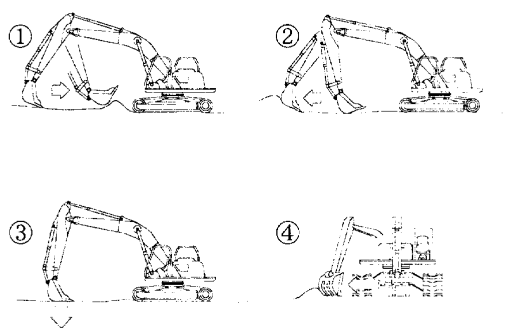

Fig.4 Main Underwater Backhoe Operations

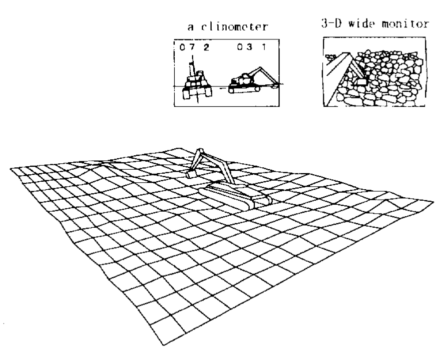

Fig.5 Underwater Backhoe on the Sea Bottom Measured with a Multi-Beam Sonar

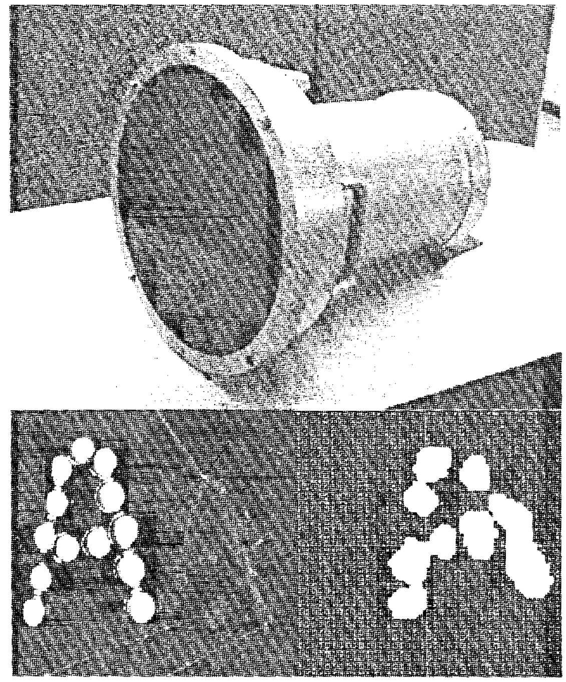

Fig.7 6-Axis Force Feedback System

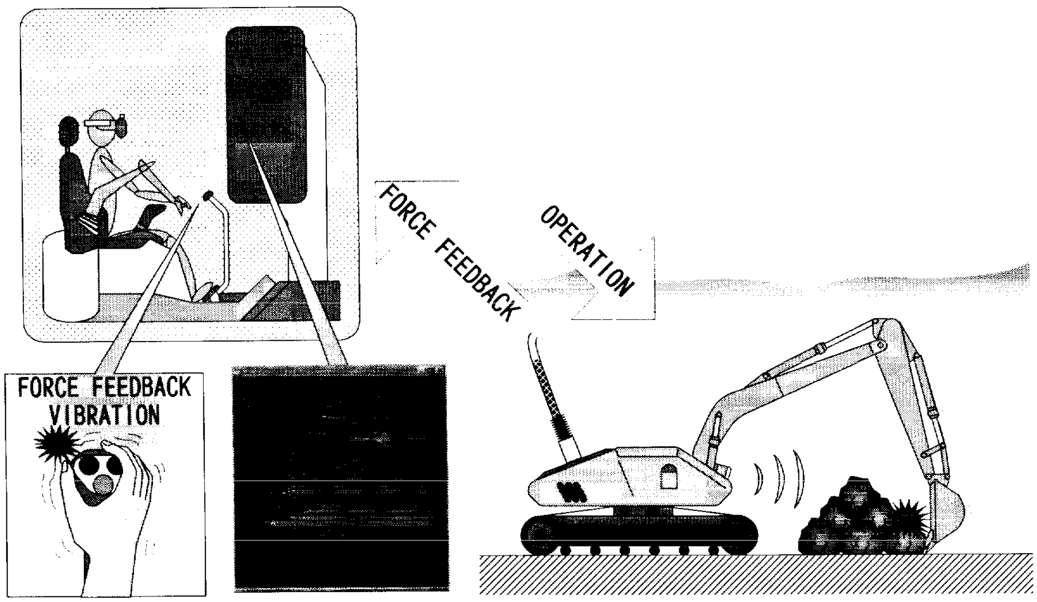

Fig.8 Total Man-Machine Interface

Table-1 Specifications of the Remotely-Controlled Underwater Backhoe

Underwater Backhoe	Operation	Unmanned Remotely-Controlled type
	Power source	Electric-Hydraulic drive
	Bucket size	$0.5m^3$
	Bucket type	Skeleton
	Working Diameter	8.5max-2.4min.(m)
	Working Depth	-30m
	Approximate size	Whole length 7.5m, body length 3.8m Whole width 2.5m, height 2.8m
	Weight	About 10ton (on the ground)
Supporting equipment	Generator	200kVA diesel
	Power supply box	
	Control panel	100kW inverter
	Cable reel	
	Clear water inlet	
	Remote control panel	
	Integrated construction control system	·Position, operation control system, monitor ·GPS receiver, telemeter ·SBL transponder ·Motion sensor(ship motion compensation) ·Underwater viewing system, monitor ·Underwater ultrasonic TV, Remote operation monitor ·Underwater TV system, monitor, Underwater light
	Control sensor	·Boom, bucket position:angle sensor ·Body direction:direction sensor ·Body inclination:inclinometer ·Bucket rotation angle:angle sensor ·Bucket load:load cell ·Mound height:pressure gauge ·Hydraulic unit:pressure gauge, temperature sensor
	Emergency support	·Manual console and seat on the body ·Air compressor for diver